

# Grand Challenges for Resilience-Based Management of Rangelands

Brandon T. Bestelmeyer<sup>1</sup> and David D. Briske<sup>2</sup>

Authors are <sup>1</sup>Research Ecologist, USDA-ARS Jornada Experimental Range and Jornada Basin LTER, New Mexico State University, Las Cruces, NM 88003, USA; and <sup>2</sup>Professor, Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843, USA.

## Abstract

The social and ecological contexts for rangeland management are changing rapidly, prompting a reevaluation of science, management, and their relationship. We argue that progression from steady-state management to ecosystem management has served the rangeland profession well, but that further development toward resilience-based management is required to ensure that ecosystem services are sustained in an era of rapid change. Resilience-based management embraces the inevitability of change and emphasizes that management should seek to guide change to benefit society. The objectives of this forum are to: 1) justify the need for adopting resilience-based management, 2) identify the challenges that will be encountered in its development and implementation, and 3) highlight approaches to overcoming these challenges. Five grand challenges confronting the adoption of resilience-based management, based upon the insights of 56 rangeland researchers who have contributed to this special issue, were identified as: 1) development of knowledge systems to support resilience-based management, 2) improvement of ecological models supporting science and management, 3) protocols to assess and manage tradeoffs among ecosystem services, 4) use of social-ecological system models to integrate diverse knowledge sources, and 5) reorganization of institutions to support resilience-based management. Resolving the challenges presented here will require the creation of stronger partnerships between ecosystem managers, science organizations, management agencies, and policymakers at local, regional, and national scales. A realistic near-term goal for achieving such partnerships is to initiate and support collaborative landscape projects. The creation of multiscaled social learning institutions linked to evolving knowledge systems may be the best approach to guide adaptation and transformation in rangelands in the coming century.

## Resumen

Los contextos ecológicos y sociales para el manejo de pastizales están cambiando rápidamente, provocando una reevaluación de la ciencia, y los vínculos entre ellos. Aquí proponemos que el reciente cambio de enfoque de un estado constante a un modelo de manejo de ecosistema ha servido bien a la profesión de manejo de pastizales, pero es necesario un cambio adicional al manejo basado en resiliencia que garantice que los servicios de los pastizales continuaran beneficiando a la sociedad en una era de cambios rápidos. El manejo basado en la resiliencia enfatiza el manejo colaborativo y el aprendizaje social para guiar la adopción y transformación en sistemas ecológico-sociales. Los objetivos de este foro son 1) justificar la necesidad para adoptar manejo basado en la resiliencia, 2) identificar los desafíos que se interpondrán en el camino para su desarrollo e implementación y 3) destacar los enfoques para superar estos desafíos. Se identificaron cinco categorías de desafíos de un manejo basado en resiliencia, usando las ideas de 55 científicos especializados en el manejo de pastizales que han contribuido especialmente a este tema: a) desarrollo de sistemas de conocimiento para soportar los sistemas de manejo basado en resiliencia, b) mejoramiento de modelos ecológicos apoyados por la ciencia y manejo, c) protocolos para evaluar y manejar el intercambio entre los servicios del ecosistema, d) uso de sistemas de perspectivas socio ecológicas para lograr una mayor participación de los interesados, y e) reorganización de las instituciones para apoyar el manejo basado en resiliencia. Se ha hecho evidente que un mayor conocimiento científico por sí mismo es insuficiente para promover los modelos de manejo basado en resiliencia en los pastizales. Las soluciones de los retos que se presentan aquí requerirán de la creación de asociaciones más fuertes entre manejadores de ecosistemas, organizaciones científicas, agencias de manejo y los creadores de políticas a nivel local, regional y nacional. La creación de instituciones sociales de aprendizaje vinculadas a la evolución de los sistemas de conocimiento es nuestra esperanza para guiar la adaptación y transformación en pastizales en el presente siglo.

**Key Words:** Adaptive management, ecosystem services, knowledge systems, postmodern science, social-ecological systems, transformation

## INTRODUCTION

We cannot solve the problems we have created with the same thinking that created them. —Ludwig (2001)

Correspondence: B. T. Bestelmeyer, USDA-ARS Jornada Experimental Range and Jornada Basin LTER, MSC 3JER, Box 30003, New Mexico State University, Las Cruces, NM 88003, USA. Email: [bbestelm@nmsu.edu](mailto:bbestelm@nmsu.edu)

The alternate editor-in-chief, M. K. Owens, was responsible for peer review and acceptance of this article.

Manuscript received 6 June 2012; manuscript accepted 4 September 2012.

Rangeland management was introduced at the turn of the 20th century to halt degradation and restore severely overgrazed ecosystems. Beginning about midcentury, it emphasized maximum sustainable production of specific commodities, primarily livestock products. In the 1990s, the emergence of ecosystem management employed a broader systems approach to address the complexity of natural resource problems (Koontz and Bodine 2008), and it continues to be an important management model. It is becoming clear, however, that rangeland management and the science supporting it must progress further to accommodate

**Table 1.** Glossary of terms and concepts presented in this synthesis (adapted from Cash et al. 2003, Chapin et al. 2010, and Reed et al. 2010).

---

<i>Adaptation</i>	—social, economic, or cultural adjustment to a change in the physical or social environment.
<i>Ecological model</i>	—simplified construct based on scientific theory and/or personal experiences to identify notions and assumptions of how systems change.
<i>Ecosystem services</i>	—benefits that humans receive from ecosystems.
<i>Knowledge system</i>	—technologies and institutions that bring together and mobilize diverse sources of information to support decision-making.
<i>Resilience</i>	—the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks.
<i>Resilience-based management</i>	—management strategies that support human well-being via adaptation and transformation of social-ecological systems to sustain the supply of ecosystem services in changing environments.
<i>Social-ecological system</i>	—system with interacting and interdependent physical, biological, and social components.
<i>Social learning</i>	—a change in understanding that extends beyond the individual to become part of broader social units or communities of practice.
<i>Transformation</i>	—fundamental change in social-ecological systems that results in the formation of novel state variables and feedbacks, ecosystem services, and livelihoods.

---

an increasing demand for ecosystem services in changing environments (Ludwig 2001; Havstad et al. 2007; Briske and Thurow 2011). Many rangelands have been altered by persistent vegetation change, soil degradation, invasive species, and changing climate; such state changes are expected to accelerate (Nandintsetseg et al. 2007; Stafford Smith et al. 2007; Williams and Jackson 2007; Dai 2011). Social change has also occurred, including stakeholders, markets, and policies influencing ecosystem management (Holmes 2002; Fernandez-Gimenez and Batbuyan 2004; Sheridan 2007). As a consequence, rangelands are increasingly being managed for diverse uses, including wildlife conservation, cropland, mine sites, and urban or renewable energy developments (Grau et al. 2008; Buenemann and Wright 2010; Belnap et al. 2012 [this issue]; Herrick et al. 2012 [this issue]), in addition to traditional services.

The accelerating rate of ecological and social change has led ecologists, ecosystem managers, and some policy makers to embrace resilience as a framework for management (Walker and Salt 2006; Chapin et al. 2009; Benson and Garmestani 2011). Resilience has been defined as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al. 2004). In practice, resilience refers to the maintenance or creation of desirable ecological states and avoiding the thresholds that lead to less desirable ones (Elmqvist et al. 2003). The maintenance of states that provide a desired combination of ecosystem services can be achieved by designing management actions to support the continually evolving characteristics of social-ecological systems (systems comprising humans and their environment; Table 1; Walker et al. 2004).

In parallel with increasing enthusiasm for resilience as a management framework, there is mounting concern that conventional approaches to scientific research will not adequately support it (Boyd and Svejcar 2009; Smith et al. 2009; Butler and Goldstein 2010). Traditional “normal” science emphasizes the use of

experiments, often at small scales, to develop generalizations concerning specific elements of ecosystem behavior (Sayre et al. 2012 [this issue]). The information produced is seldom directly relevant to management because there are few incentives within the scientific community to apply this knowledge to specific cases faced by managers (Ludwig et al. 1993, 2001). The minimal predictive capacity of individual theories, narrow spatial and temporal scales examined, and infrequent consideration of societal and administrative complexities experienced by managers and policymakers further limit the use of science as a guide for management (Ludwig et al. 1993; Briske 2012; Driscoll and Lindenmayer 2012). More often, anecdotal evidence and past experiences are used as guides instead (Pullen et al. 2004; Lawton 2007).

The “post-normal” (Funtowicz and Ravetz 1993) or “post-modern” (Allen et al. 2001) approach to science could more effectively promote resilience by virtue of its emphasis on biophysical and social contexts rather than broadly applicable generalities. Its aim is to use the tools of science to address the complexities of specific localities, and it acknowledges that the problems structuring scientific inquiry emerge from human perspectives (Sayre et al. 2012 [this issue]). This approach to science underpins what has become known as “resilience-based” management or “ecosystem stewardship” (Chapin et al. 2009, 2010). In contrast to steady-state or ecosystem management approaches, resilience-based management embraces the inevitability of social and environmental change, and management seeks to guide change to benefit society (Table 2). This concept is broader than the antecedent ecological resilience concept (Holling 1973) because it emphasizes the properties of entire social-ecological systems, rather than the persistence of particular ecological states linked to historical conditions. The term “resilience” in resilience-based management pertains to societal well-being and not necessarily to particular ecological or social structures; indeed, change in these structures is often necessary to sustain well-being (Walker et al. 2004). While resilience-based management offers clear advantages in ecosystems experiencing rapid social-ecological change, methods to implement it are only now emerging.

We outline five grand challenges associated with the development of resilience-based management for rangeland systems. We garnered ideas from papers within this special issue, collectively representing the insights of 56 rangeland researchers reflecting on the successes and failures of the rangeland profession over the past century. We also consulted synthetic works in topic areas addressed by these and other authors to review each challenge. Rather than listing a large number of specific concerns (e.g., Sutherland et al. 2009; Fleishman et al. 2011), we identified a small number of broad (i.e., grand) challenges that are of particular importance to rangeland management as well as specific issues embedded in those challenges (e.g., Morton et al. 2009). Our hope is that the insights and recommendations in this special issue may catalyze a reevaluation of educational programs, research agendas, and policies.

## CHANGING CONTEXT FOR RANGELAND SCIENCE AND MANAGEMENT

The Earth’s social-ecological systems have entered an era of unprecedented change (Rockstrom et al. 2009; Chapin et al.

**Table 2.** Seven distinguishing attributes of steady state, ecosystem, and resilience-based management models (modified from Chapin et al. 2009).

	Steady state management	Ecosystem management	Resilience-based management
<i>Ecological models</i>	Succession–retrogression	State-and-transition, rangeland health	Multiple social-ecological systems/ novel ecosystems
<i>Reference condition</i>	Historic climax plant community	Historic climax plant community, including historical range of variation	Landscapes with maximum options for ecosystem services
<i>Role of humans</i>	Use ecosystems	Part of ecosystems	Direct trajectories of ecosystem change
<i>Ecosystem services</i>	Meat and fiber products	Several ecosystem services	Options for diverse ecosystem services
<i>Management goals</i>	Sustain maximum yield of commodities	Sustain multiple uses	Sustain capacity of social-ecological systems to support human well-being
<i>Science-management linkages</i>	Top-down from management agencies	Top-down from management agencies	Multiscaled social learning institutions
<i>Knowledge systems</i>	Management experience and agricultural experiments	Multidisciplinary science and ecological experiments	Collaborative groups, spatially referenced, updatable database systems

2010). Many of these changes have complex, multicausal origins that have developed substantial momentum, and their ultimate consequences are largely unknown. Three of the most pressing global change issues are 1) a rapidly growing human population and accelerating land use change, 2) the capacity for current agricultural systems to meet increasing food demand sustainably, and 3) the ability of agricultural production systems to adapt to climate change (Millennium Ecosystem Assessment 2005; Dietz et al. 2007). The unprecedented rate of change associated with these issues raises the question, “What will be the future role of rangelands in supplying human societies with ecosystem services?” Increased production efficiency may be able to meet the increased food demand, including a substantial increase in meat production, but greater uncertainty resides in the resulting changes to other ecosystem services (Godfray et al. 2010; Gomiero et al. 2011). Consequently, there is a clear need for a science and management approach that embraces uncertainty and that can continuously reevaluate strategies and outcomes in response to new information and unanticipated events.

The rangeland profession has already embarked upon a path toward resilience-based management in some respects. In the past 25 yr, the profession has undergone a shift from steady state to ecosystem management within the United States (Table 2). Steady state management sought to maximize the sustainable yield of a few specific commodities based upon the succession–retrogression model of rangeland assessment. In this model, management emphasized maintenance of a single reference state characterized by the historical conditions at the time of European settlement (e.g., historic climax plant community; Dyksterhuis 1949; Briske et al. 2003). This approach was supported by ecological principles derived from simple experiments, often emphasizing individual plant responses, and this information was delivered in a top-down fashion via federal agencies (Briske et al. 2011). Recognition of accelerating ecological change, demand for more diverse services, and increasing political pressures in the 1970s and 1980s catalyzed a shift toward an ecosystem management model. This shift was paralleled by a focus on ecological processes (especially soil functions and natural disturbance) supporting a historical range of variation and rangeland health, commensurate with the expectation that rangelands would provide multiple services to an increasingly diverse group of

stakeholders (National Research Council 1994). Ecosystem management was supported by more comprehensive ecological information supplied by a rapidly growing ecology discipline, but it was still delivered as top-down regulation from the US Forest Service and Bureau of Land Management and as recommendations and incentives from agricultural extension programs and the Natural Resources Conservation Service. Priorities on ecosystem services, especially on public rangelands, were sought through organizations such as resource advisory groups but often involved litigation (Sheridan 2007).

The recent shift from steady state to ecosystem management has had a transformative influence on all aspects of rangeland science and management as evidenced by modified funding priorities and research agendas, restructuring of academic rangeland programs, development of large integrated research teams, and most recently the Rangeland Conservation Effects Assessment (Briske and Thurow 2011). While use of the ecosystem management model is viewed as positive and necessary, it is also perceived as insufficient to guide rangeland management into a future characterized by rapid and unprecedented change (Ludwig 2001; Chapin et al. 2009). Aspects of ecosystem management will continue to serve the profession well, but resilience-based management may provide a more effective means for coping with accelerating change and deepening uncertainty (Table 2).

## GRAND CHALLENGES

Our synthesis identifies five grand challenges that are likely to be encountered in the progression from ecosystem management to resilience-based management. For each challenge, we provide a brief rationale, identify key barriers to development and adoption, and recommend approaches for implementation. We regard the initial challenge—development of knowledge systems to support adaptation and transformation—as the overarching challenge.

### Challenge 1. Develop Knowledge Systems to Support Adaptation and Transformation

**Rationale.** The primary goal of resilience-based management is to generate knowledge that guides adaptation and transfor-

**Table 3.** Examples of existing knowledge systems or components supporting rangeland management.

Name	Web site	Reference
Ecological Site Descriptions	<a href="http://esis.sc.egov.usda.gov">http://esis.sc.egov.usda.gov</a>	Brown 2010
Web Soil Survey	<a href="http://websoilsurvey.nrcs.usda.gov">http://websoilsurvey.nrcs.usda.gov</a>	N/A
USDA Plants Database	<a href="http://plants.usda.gov">http://plants.usda.gov</a>	N/A
Global Rangelands Knowledge System	<a href="http://globalrangelands.org">http://globalrangelands.org</a>	Hutchinson et al. 2011
Landscape Toolbox	<a href="http://www.landscapetoolbox.org">http://www.landscapetoolbox.org</a>	Karl et al. 2011
Desert Knowledge Cooperative Research Centre	<a href="http://www.desertknowledgecrc.com.au">http://www.desertknowledgecrc.com.au</a>	Stafford Smith et al. 2008
Livestock Early Warning Systems	<a href="http://cnrit.tamu.edu">http://cnrit.tamu.edu</a>	Stuth et al. 2005

mation of social-ecological systems. Adaptation requires adjusting management, policies, and social institutions to changing conditions such that the current social-ecological system is maintained. Alternatively, transformation acknowledges that the current social-ecological system may be untenable (e.g., due to large societal or climatic changes) and therefore the management objectives and institutions should be radically changed to promote human well-being (Table 1; Folke et al. 2010). Integration of knowledge sources, including local, professional, and scientific, will be essential to support adaptation and especially transformation (Stafford Smith et al. 2007; Reid et al. 2010; Weible et al. 2010). The requirement for place-based, current, and actionable information places a greater emphasis on stakeholder involvement in knowledge generation than has existed in the past (Juntti et al. 2009). Partnerships among diverse stakeholders and scientists may more effectively support adaptation and transformation than does the traditional research approach.

Relevant information must be organized, made available, and used via knowledge systems so that it can guide adaptation and transformation. Knowledge systems entail the technologies and institutions that motivate and harness diverse sources of information for decision-making (Cash et al. 2003). They provide the means to use local knowledge, research products (e.g., experimental results, soil maps, climate forecasts, remotely sensed data) and the collaborative development of new information (e.g., Polasky et al. 2011). In the rangeland profession, several existing, partial, or incipient knowledge systems are available (Table 3). Knowledge systems circumscribe databases that contain information (e.g., Ecological Site Descriptions [ESDs]), as well as the personal interactions that aid its use (e.g., scientist–manager partnerships). Such knowledge systems are critical to the development of effective management strategies and policies because, ideally, they can incorporate information derived from both successes and failures to facilitate social learning (Reed et al. 2010).

**Barriers.** In spite of the massive amount of existing data and information, they are often not organized and available in a useful form, reflecting a general problem in global data management and delivery (e.g., Mervis 2012). Furthermore, rapid change in land uses and ecosystem states demand rapidly updated information systems that are currently limited (Karl et al. 2012 [this issue]). Finally, institutions supporting the generation and use of collaborative information to design and test management actions are poorly developed, even in the United States where substantial public investments have been made in rangeland conservation over the past several decades (Briske and Thurow 2011). Specific barriers to successful

knowledge systems are numerous, including insufficient recognition of information needs and user characteristics, limited data collection and management resources, and an unwillingness to share information and power (Cortner et al. 1998; Koontz and Bodine 2008).

**Approaches.** Several specific strategies to improve the availability and use of information have been proposed including 1) increasing connectivity across databases so that various information sources can be linked and discovered, 2) linkage of information to spatial data so that information can be searched by location and obtained via mobile devices, 3) use of crowdsourcing technologies to obtain local knowledge and information on current processes, 4) advances in remote sensing and spatial data products to better reflect processes of interest, particularly those described in ecological models, 5) the development of user-friendly, modular modeling tools that can be matched to local concerns and information, and 6) updated training curricula for rangeland users (see Abbott et al. 2012 [this issue]; Derner et al. 2012 [this issue]; Karl et al. 2012 [this issue]). Landscape-scale collaborative projects can provide a forum for developing knowledge systems and for applying them via tests of management actions. Specific mechanisms to promote the continued development of knowledge systems include:

- Establish durable institutions and/or programs to support knowledge systems and their continued evolution over the long term, including government land management agencies, universities, or international nongovernmental organizations.
- Support the organization of regional or landscape collaborative groups to develop local knowledge systems via “bridging organizations,” including research agencies, universities, and professional societies (e.g., Society for Range Management, Society for Ecological Restoration, and The Quivira Coalition).
- Require structured monitoring and databasing for all major federal expenditures on land management.
- Support scientists’ involvement with collaborative groups.

## Challenge 2. Improve Models of Ecological Systems

**Rationale.** Rangeland science and management are ultimately based on ecological models, often implicitly in the form of conceptual models or “mental models” (sensu Abel et al. 1998) that are sometimes supported by scientific models. Mental models are personal, context-dependent representations of ecological systems that humans use as a basis for decision-making (Jones et al. 2011). Scientific models are simplified



constructs that emanate from theory to identify explicitly the notions, assumptions, and evidence for how systems can change (Pickett et al. 2007). In making management decisions, the specific model used is important because it determines both the expected ecosystem response to particular actions, as well as the strategies to attain desired conditions (e.g., Lynam and Stafford Smith 2004; Bedunah and Angerer 2012 [this issue]). In this capacity, state-and-transition models (STMs) are viewed as useful tools because they integrate personal and scientific knowledge in a formal and site-specific way that can be directly accessed by land managers (Knapp et al. 2011a).

**Barriers.** The use of STMs and related formal, integrative models (e.g., conceptual ecological or simulation models) to support resilience-based management is limited because they are often not updated with new knowledge, focus on ecosystem responses relative to historical variability rather than projecting future outcomes, emphasize a narrow range of ecosystem attributes and services, and are restricted to spatial scales of individual ecological sites (Ash et al. 2012 [this issue]; Belnap et al. 2012 [this issue]; Fuhlendorf et al. 2012 [this issue]; Herrick et al. 2012 [this issue]). Furthermore, models pertaining to specific rangeland areas often do not adequately represent the effects of spatial heterogeneity in different variables at different scales, nonlinear relationships among key variables, and local knowledge (Bestelmeyer et al. 2011a, 2011b; Peters et al. 2012 [this issue]). These problems limit our ability to use ecological knowledge represented in models to guide resilience-based management, and they reinforce doubt about the utility of formal models for management.

**Approaches.** STMs and other modeling efforts could be made more prospective, more explicitly multiscaled, and more directly linked to diverse ecosystem services. For example, STMs could more explicitly include information about potential changes in ecological states, or the ecological states that will be available, with anticipated changes in drivers and land uses (Bradley and Wilcove 2009; Bestelmeyer 2012; Peters et al. 2012 [this issue]). Efforts to model landscape change at broader spatial scales must also be distilled into easily understood tools by developing general regional or landscape conceptual models (Bestelmeyer et al. 2011b). STMs must also integrate ecosystem attributes other than plant community composition and aboveground primary production if they are to be used by diverse stakeholders; this integration could be accomplished by linking the attributes in STMs and landscape models to the products of other kinds of models on a regional basis (e.g., sage grouse habitat requirements; Evers et al. 2011). Finally, we must make institutional commitments to test and update collaboratively the assumptions of ecological models via monitoring of management actions (Knapp et al. 2011b; Derner et al. 2012 [this issue]). Several critical tasks to be addressed include:

- Map relevant sources of rangeland heterogeneity, particularly soils and ecological states, where such information is lacking so that information can be linked to similar classes of land (Sanchez et al. 2009; Herrick et al. 2012 [this issue]; Steele et al. 2012).
- Incorporate landscape-level effects to explain site-level variations in ecosystem properties (Peters et al. 2006; Bestelmeyer et al. 2011b).

- Develop and link models at different spatial scales and for different attributes, including plant communities, water resources, and wildlife populations (e.g., Letnic and Dickman 2010; Vivoni 2012).
- Produce models that anticipate the broad-scale consequences of incipient/potential land use changes (Herrick et al. 2012 [this issue]) or projected changes in climate (Bradley and Wilcove 2009).

### Challenge 3. Assess and Manage Tradeoffs Among Ecosystem Services

**Rationale.** Ecosystem services refer to the ecosystem functions that are useful to humans (Kremen 2005; Millennium Ecosystem Assessment 2005). Due to their expansive area and great heterogeneity, rangelands provide an unusual diversity of ecosystem services, including forage for livestock production, habitat for wildlife, biodiversity, open space, carbon sequestration, fresh water supply, and cultural services (Havstad et al. 2007). Various stakeholders value these services differently, and management actions may favor some services over others. Consequently, protocols are needed to assess potential tradeoffs and synergies between ecosystem services as a basis for decision-making (Bennett et al. 2009). For example, some management actions may favor multiple ecosystem services simultaneously, whereas others may produce tradeoffs between different services (Olenick et al. 2005; Dunn et al. 2010; Archer et al. 2011). Strategies to restore historical states or to promote transformation to novel states could be evaluated based upon the ecosystem services provided by the available states relative to estimated restoration costs, but such evaluations typically vary among stakeholders (Belnap et al. 2012 [this issue]; Monaco et al. 2012 [this issue]). Evaluation of tradeoffs must also consider changes in attributes such as soil quality since specific services may provide short-term benefits that constrain options for other services in the future (e.g., conversion of rangeland to dryland crop production; Herrick et al. 2012 [this issue]).

**Barriers.** The profession has had a long history of emphasizing provisioning services (food and fiber), but other categories of ecosystem services have only recently been fully acknowledged (Havstad et al. 2007; Tanaka et al. 2011). Consequently, limited investments in the identification and measurement of the full complement of ecosystem services have precluded consideration of synergies and tradeoffs among various services in management decisions (e.g., Fuhlendorf et al. 2012 [this issue]).

**Approaches.** STMs and land classifications such as ecological sites or Terrestrial Ecosystem Units could be redesigned to convey information about multiple ecosystem services (Herrick et al. 2006; Bestelmeyer et al. 2011b). Ecological states or broader-scaled land units can then be represented with regard to the “bundles” of ecosystem services they provide (Raudsepp-Hearne et al. 2010), rather than judged to be universally healthy or degraded, as is the case for steady state and ecosystem management models. Recent efforts to document multiple ecosystem services in rangelands could be expanded (Eviner et al. 2012) and linked to the development of STMs and ESDs. These tools can help stakeholders recognize not only the short-term tradeoffs among services, but also complementarities

among the services provided by different locations in a landscape and limitations for attaining particular services at specific locations. It is also important to recognize that ecosystem services can be directly manipulated through scientific innovation and agricultural technology, such as by increasing the palatability of shrubs to livestock (Estell et al. 2012 [this issue]). Critical tasks involved with this challenge are:

- Develop methods for measurement of different ecosystem services provided by ecological sites, states, or mosaics of states (Brown and MacLeod 2011; Eviner et al. 2012).
- Create protocols for the evaluation of tradeoffs among ecosystem services in the selection of management decisions (Raudsepp-Hearne et al. 2010).
- Link information about ecosystem services and tradeoffs to ecological models and land classifications (Nelson et al. 2009).

#### Challenge 4. Develop Social-Ecological System Perspectives

**Rationale.** Although it is generally recognized that rangelands function as social-ecological systems, societal perspectives and their interactions with ecological processes have only recently been considered in research and management. Integrated social-ecological perspectives have sought to remedy this shortcoming by considering the effects of attitudes, policies, or incentives on biophysical change (Grimm et al. 2000; Collins et al. 2011) and by considering societal and biophysical properties simultaneously (Reynolds et al. 2007; Stafford Smith 2008). The significance of social-ecological perspectives is most evident when social, cultural, and economic circumstances generate management decisions that do not appear logical from the perspective of environmental scientists. Conflicting interpretations of the effectiveness of rotational grazing between scientists and some managers is one manifestation of this problem (Boyd and Svejcar 2009; Briske et al. 2011). The debate originated in part from addressing a complex issue with a narrow experimental approach that focused exclusively on ecological processes, without reference to management goals and capabilities.

**Barriers.** In spite of the potential value of social-ecological approaches, they have proven difficult to implement (Brand and Jax 2007; Briske et al. 2011; Brunson 2012 [this issue]). This difficulty originates from historical academic traditions that have separated biophysical and social science and constrained inquiry into social processes associated with natural resource management (Weichelgartner and Kasperson 2010), recently manifested in calls to separate social science from the natural sciences in federal funding (Coburn 2011). As a consequence, these two disciplines have developed unique cultures, methods of inquiry, and information bases that have proven difficult to integrate in support of resilience-based management (Brunson 2012 [this issue]). In addition to these research challenges, the establishment of successful collaborative groups can be equally demanding with regard to trust, power sharing, and information transfer, especially in the context of disputed or uncertain tradeoffs among desired ecosystem services or land uses (e.g., Paulson 1998; Walker and Hurley 2004; Belnap et al. 2012 [this issue]).

**Approaches.** Participatory development and testing of hypotheses concerning ecosystem behaviors and services—involv-

ing scientists, managers, and other stakeholders—can provide an effective way to employ social-ecological perspectives (e.g., Waltner-Toews et al. 2003; Duff et al. 2009; Morton et al. 2010; Briske et al. 2011). This approach could be facilitated by the development of social-ecological conceptual models, involving greater input by social scientists (Brunson 2012 [this issue]). Recent approaches in the collaborative development of STMs can help identify key ecosystem services of interest (Knapp et al. 2011b), and cooperative testing and interpretation of management actions can be used to assess the assumptions and knowledge represented in models (Sheley et al. 2006; Boyd and Svejcar 2009). General guidelines for successful collaborative interactions have recently been reviewed (Reed et al. 2008; Duff et al. 2009; Butler and Goldstein 2010; Measham et al. 2011). Collaborative landscape management projects discussed by these authors provide a workable procedure to develop social-ecological perspectives in rangelands. Specific needs include:

- Develop general guidelines for the establishment and maintenance of collaborative projects involving environmental and social scientists, managers, and varied stakeholders (Measham et al. 2011).
- Produce social-ecological models for various landscapes, including identification of critical social metrics, as well as their interactions with biophysical components (Brunson 2012 [this issue]).
- Provide cross-disciplinary training opportunities to link social and environmental sciences (Reed 2008; Abbott et al. 2012 [this issue]; Briske 2012).
- Establish durable bridging institutions to maintain interactions among scientists, managers, stakeholders, and policymakers (Berkes 2009).

#### Challenge 5. Build Organizations to Promote Resilience-Based Management

**Rationale.** It is clear that scientific knowledge alone is insufficient to promote resilience-based management (Ludwig et al. 2001; Marx et al. 2007). Resolving the challenges presented above will require the creation of stronger partnerships between science organizations, management agencies, policymakers, land owners, and sponsors at local, regional, and national to international levels to create learning communities or “social learning institutions” (Smith et al. 2009). The prevailing view is that these learning communities are most successful when initiated locally or regionally, but initiation often requires influence and support from national and international levels, in the form of policies, incentives, and information (Chapin et al. 2009).

**Barriers.** The recognition that policies based on steady-state thinking are of diminishing value represents an important step toward implementation of resilience-based management (Folke 2006). Nonetheless, existing institutions and individuals often do not readily admit to error, rapidly change long-standing norms, or wish to share power. Similarly, science must also be prepared to admit its limits because many complex environmental problems involve values, equity, and social justice that are not addressed by current methods (Ludwig 2001; Brunson 2012 [this issue]). Partnerships capable of generating and transferring

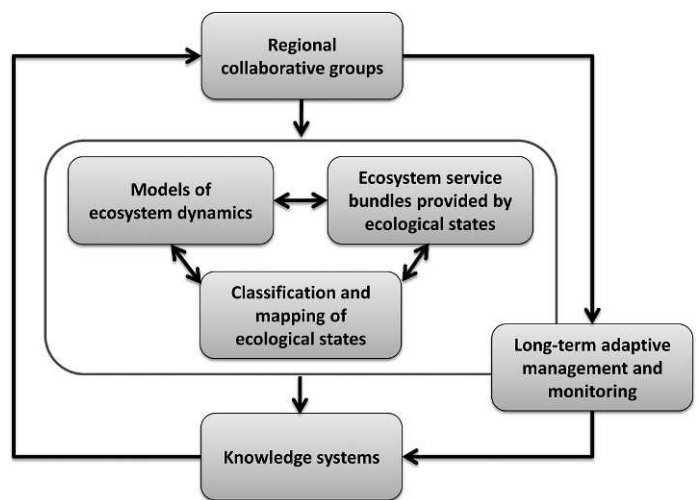
knowledge are often constrained by systems of academic training and incentives, funding allocations, institutional cultures, and legal obligations (Koontz and Bodine 2008; Briske 2012). The existence of “stove pipes” (isolated programs in large bureaucracies) tends to fragment knowledge, impede information flow, and produce poor decisions (Cortner et al. 1998). A centralized structure controlling both power and financial resources often supports a top-down approach, which is recognized as an impediment to resilience-based management.

**Approaches.** A broad institutional framework, including a coordinating entity, is required to organize learning communities and support knowledge systems. Partners in the learning community must be willing to identify personnel that 1) are open minded and willing to share power, 2) able to lead teams in addressing broad natural resource management issues, and 3) communicate frequently with partnering agencies and institutions (Cortner et al. 1998; Juntti et al. 2009). These learning teams may be most effectively organized around landscape-level monitoring programs designed to evaluate and improve management decisions. Collaborative landscape projects would strengthen the mission of federal science and management agencies in the United States by serving a greater cross-section of stakeholders and increasing the likelihood of successful management outcomes. These collaborations should include educational awareness programs to ensure the broadest possible public participation. Specific strategies include:

- Replace top-down management prescriptions and policies with directives to establish flexible, collaborative landscape management programs.
- Engage diverse stakeholders, including private, state, and federal, at local, regional, and national levels, in collaborative programs and decision-making processes.
- Look beyond immediate symptoms and responses to identify and manage conditions ultimately responsible for the problems confronting social-ecological systems.

## AN APPROACH FOR IMPLEMENTING RESILIENCE-BASED MANAGEMENT

We outline a broad approach that could be used to guide development and implementation of resilience-based management (Fig. 1). Management begins with the establishment of collaborative groups that work with both scientific and local knowledge to identify specific issues of interest and key attributes within social-ecological systems. Collaborative groups would select or develop suitable ecological models linked to classifications and maps that portray predicted ecosystem responses in a spatially explicit manner (i.e., ecological sites, ecological states, and landscape mosaics). The ecosystem services that are desired from ecological states—either independently or in combinations within a landscape—help determine the utility of specific models, spatial data needs, and potential management approaches. These interlinked sources of information are combined with a process of collaborative interpretation and consensus building within a knowledge system. Project-specific knowledge systems could be organized and maintained by technical personnel associated with science organizations, federal agencies, or nongovernmental organizations and could draw upon information contained



**Figure 1.** A sequence of steps for implementing resilience-based management beginning with the formation of regional collaborative groups. Models of ecosystem dynamics, assessments of ecosystem services of interest, and classification and mapping are interlinked activities, represented by the box circumscribing them.

within evolving global knowledge systems. Decisions achieved via the knowledge system, looping back to the collaborative group (Fig. 1), define the expected responses to management actions within specific land areas. Long-term adaptation or transformation efforts (given that change often occurs gradually over several years to decades) are applied and then monitored, updating the information in the knowledge system and the perceptions and actions of stakeholders. Elements of this approach reflect ongoing practice for some natural resource management activities, such as the Southwest Jemez Mountains Collaborative Forest Landscape Restoration Program.<sup>1</sup> Development agencies, land management agencies, and national and private granting agencies could prioritize funding for collaborative projects based on evaluations of need and the preconditions for success. A network of collaborative landscape projects, recognizing their common elements for comparison and training, would advance a science of resilience-based management in rangelands (e.g., Walker et al. 2009; Susskind et al. 2012).

## MANAGEMENT IMPLICATIONS

Current applications of ecosystem management in rangelands often feature weak connections between science and decision-making, programmatically driven actions that are not critically evaluated and updated, and valuation of knowledge in terms of the political power it conveys (Ludwig 2001; Chapin et al. 2010; Briske et al. 2011). A management framework based on these attributes will not enable societies to respond in reasoned and purposeful ways to rapid change and increasing uncertainty (Carpenter et al. 2009). Here we argue that progression from ecosystem management toward resilience-based management within the rangeland profession provides the greatest opportunities for the continued supply of diverse services from rangelands (Table 2). Resilience-based management recognizes

<sup>1</sup>[http://www.fs.fed.us/r3/sfe/jemez\\_mtn\\_rest/docs.htm](http://www.fs.fed.us/r3/sfe/jemez_mtn_rest/docs.htm)



that change is inevitable; it empowers managers with the responsibility to guide change and identify the potential for adaptation or transformation of social-ecological systems. Multiscaled social learning institutions, focused on the uniqueness of particular social-ecological systems, but supported by government institutions and industry, will be required to implement resilience-based management. Social learning in rangelands can be achieved most directly by collaborative evaluation of the consequences of management and policy actions via monitoring programs, and by developing updatable, spatially explicit databases to make such information available to users. The initiation and support of collaborative landscape projects in suitable settings provide realistic and attainable near-term goals that can inspire the longer-term institutional changes that will be needed to enable the broad application of resilience-based management.

## LITERATURE CITED

- ABBOTT, L. B., K. L. LAUNCHBAUGH, AND S. EDINGER-MARSHALL. 2012. Range education in the 21st century: striking the balance to maintain a relevant profession. *Rangeland Ecology & Management* 65:647–653.
- ABEL, N., H. ROSS, AND P. WALKER. 1998. Mental models in rangeland research, communication and management. *The Rangeland Journal* 20:77–91.
- ALLEN, T. H. F., J. A. TAINTER, J. C. PIRES, AND T. W. HOEKSTRA. 2001. Dragnet ecology—“Just the facts, Ma’am”: the privilege of science in a postmodern world. *BioScience* 51:475–485.
- ARCHER, S. R., K. W. DAVIES, T. E. FULBRIGHT, K. C. MCDANIEL, B. P. WILCOX, AND K. I. PREDICK. 2011. Brush management as a rangeland conservation strategy: a critical evaluation. In: D. D. Briske [ed.]. *Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps*. Lawrence, KS, USA: Allen Press. p. 105–170.
- ASH, A., P. THORNTON, C. STOKES, AND C. TOGTOHYN. 2012. Is proactive adaptation to climate change necessary in grazed rangelands? *Rangeland Ecology & Management* 65:563–598.
- BEDUNAH, D. J., AND J. P. ANGERER. 2012. Rangeland degradation, poverty, and conflict: how can rangeland scientists contribute to effective responses and solutions? *Rangeland Ecology & Management* 65:606–612.
- BELNAP, J., J. A. LUDWIG, B. P. WILCOX, J. L. BETANCOURT, W. R. J. DEAN, B. D. HOFFMANN, AND S. J. MILTON. 2012. Introduced and invasive species in novel rangeland ecosystems: friends or foes? *Rangeland Ecology & Management* 65:569–578.
- BENNETT, E. M., G. D. PETERSON, AND L. J. GORDON. 2009. Understanding relationships among multiple ecosystem services. *Ecology Letters* 12:1394–1404.
- BENSON, M. H., AND A. S. GARMESTANI. 2011. Can we manage for resilience? The integration of resilience thinking into natural resource management in the United States. *Environmental Management* 48:392–399.
- BERKES, F. 2009. Evolution of co-management: role of knowledge generation, bridging organizations and social learning. *Journal of Environmental Management* 90:1692–1702.
- BESTELMEYER, B. T. 2012. Is the historical range of variation relevant to rangeland management? In: J. Wiens, G. Hayward, H. Safford, and C. Giffen [eds.]. *Historical environmental variation in conservation and natural resources management: past, present, and future*. West Sussex, UK: Wiley-Blackwell. p. 289–296.
- BESTELMEYER, B. T., A. M. ELLISON, W. R. FRASER, K. B. GORMAN, S. J. HOLBROOK, C. M. LANEY, M. D. OHMAN, D. P. C. PETERS, F. C. PILLSBURY, A. RASSWEILER, R. J. SCHMITT, AND S. SHARMA. 2011a. Analysis of abrupt transitions in ecological systems. *Ecosphere* 2:129. doi:10.1890/ES11-00216.1
- BESTELMEYER, B. T., X. B. WU, J. R. BROWN, S. D. FUHLENDORF, AND G. FULTS. 2011b. Landscape approaches to rangeland conservation practices. In: D. D. Briske [ed.]. *Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps*. Lawrence, KS, USA: Allen Press. p. 337–370.
- BOYD, C. S., AND T. J. SVEJCAR. 2009. Managing complex problems in rangeland ecosystems. *Rangeland Ecology & Management* 62:491–499.
- BRADLEY, B. A., AND D. S. WILCOVE. 2009. When invasive plants disappear: transformative restoration possibilities in the Western United States resulting from climate change. *Restoration Ecology* 17:715–721.
- BRAND, F. S., AND K. JAX. 2007. Focusing meaning(s) of resilience: resilience as a descriptive concept and a boundary object. *Ecology and Society* 12(1):23. Available at: <http://www.ecologyandsociety.org/vol12/iss1/art23/>.
- BRISKE, D. D. 2012. Translational science partnerships: key to environmental stewardship. *BioScience* 62:449–450.
- BRISKE, D. D., J. D. DERNER, D. G. MILCHUNAS, AND K. W. TATE. 2011. An evidence-based assessment of prescribed grazing practices. In: D. D. Briske [ed.]. *Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps*. Lawrence, KS, USA: Allen Press. p. 22–74.
- BRISKE, D. D., S. D. FUHLENDORF, AND F. E. SMEINS. 2003. Vegetation dynamics on rangelands: a critique of the current paradigms. *Journal of Applied Ecology* 40:601–614.
- BRISKE, D. D., AND T. L. THUROW. 2011. Executive summary: the next generation of conservation practice standards. In: D. D. Briske [ed.]. *Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps*. Lawrence, KS, USA: Allen Press. p. 9–20.
- BROWN, J. R. 2010. Ecological sites: their history, status, and future. *Rangelands* 32(6):5–8.
- BROWN, J., AND N. MACLEOD. 2011. A site based approach to delivering rangeland ecosystem services. *The Rangeland Journal* 33:99–108.
- BRUNSON, M. W. 2012. The elusive promise of social-ecological approaches to rangeland management. *Rangeland Ecology & Management* 65:632–637.
- BUEENEMANN, M., AND J. WRIGHT. 2010. Southwest transformation: eras of growth and land change in Las Cruces, New Mexico. *Southwest Geographer* 14:57–87.
- BUTLER, W. H., AND B. E. GOLDSTEIN. 2010. The US fire learning network: springing a rigidity trap through multi-scalar collaborative networks. *Ecology and Society* 15(3):21. Available at: <http://www.ecologyandsociety.org/vol15/iss3/art21/>.
- CARPENTER, S. R., C. FOLKE, M. SCHEFFER, AND F. WESTLEY. 2009. Resilience: accounting for the noncomputable. *Ecology and Society* 14(1):13. Available at: <http://www.ecologyandsociety.org/vol14/iss1/art13/>.
- CASH, D. W., W. C. CLARK, F. ALCOCK, N. M. DICKSON, N. ECKLEY, D. GUSTON, J. JÄGER, AND R. MITCHELL. 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences USA* 100:8086–8091.
- CHAPIN, F. S., III, S. R. CARPENTER, G. P. KOFINAS, C. FOLKE, N. ABEL, W. C. CLARK, P. OLSSON, D. M. STAFFORD SMITH, B. WALKER, O. R. YOUNG, F. BERKES, R. BIGGS, J. M. GROVE, R. L. NAYLOR, E. PINKERTON, W. STEPHEN, AND F. J. SWANSON. 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in Ecology and Evolution*. 25:241–249.
- CHAPIN, F. S., III, C. FOLKE, AND G. P. KOFINAS. 2009. A framework for understanding change. In: F. S. Chapin III, G. P. Kofinas, and C. Folke [eds.]. *Principles of ecosystem stewardship: resilience-based natural resource management in a changing world*. New York, NY, USA: Springer. p. 3–28.
- COBURN, T. A. 2011. The National Science Foundation: under the microscope. Oversight report. Available at: [http://coburn.senate.gov/public/index.cfm?a=Files.Serve&File\\_id=2dccc06d-65fe-4087-b58d-b43ff68987fa](http://coburn.senate.gov/public/index.cfm?a=Files.Serve&File_id=2dccc06d-65fe-4087-b58d-b43ff68987fa). 73 p.
- COLLINS, S. L., S. R. CARPENTER, S. M. SWINTON, D. E. ORENSTEIN, D. L. CHILDERS, T. L. GRAGSON, N. B. GRIMM, J. M. GROVE, S. L. HARLAN, J. P. KAYE, A. K. KNAPP, G. P. KOFINAS, J. J. MAGNUSON, W. H. McDOWELL, J. M. MELACK, L. A. OGDEN, G. P. ROBERTSON, M. D. SMITH, AND A. C. WHITMER. 2011. An integrated conceptual framework for long-term social-ecological research. *Frontiers in Ecology and the Environment* 9:351–357.
- CORTNER, H. J., M. G. WALLACE, S. BURKE, AND M. A. MOOTE. 1998. Institutions matter: the need to address the institutional challenges of ecosystem management. *Landscape and Urban Planning* 40:159–166.
- DAI, A. 2011. Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change* 2:45–65. doi:10.1002/wcc.81
- DERNER, J. D., D. J. AUGUSTINE, J. C. ASCOUGH II, AND L. R. AHUJA. 2012. Opportunities for increasing utility of models for rangeland management. *Rangeland Ecology & Management* 65:623–631.
- DIETZ, T., E. A. ROSA, AND R. YORK. 2007. Driving the human ecological footprint. *Frontiers in Ecology and Environment* 5:13–18.
- DRISCOLL, D. A., AND D. B. LINDENMAYER. 2012. Framework to improve the application of theory in ecology and conservation. *Ecological Monographs* 82:129–147.



- DUFF, D. G., D. GARNETT, P. JACKLYN, J. LANDSBERG, J. LUDWIG, J. MORRISON, P. NOVELLY, D. WALKER, AND P. WHITEHEAD. 2009. A collaborative design to adaptively manage for landscape sustainability in north Australia—lessons from a decade of cooperative research. *Landscape Ecology* 24:1135–1143.
- DUNN, B. H., A. J. SMART, R. N. GATES, P. S. JOHNSON, M. K. BEUTLER, M. A. DIERSEN, AND L. L. JANSSEN. 2010. Long-term production and profitability from grazing cattle in the northern mixed grass prairie. *Rangeland Ecology & Management* 63:233–242.
- DYKSTERHUIS, E. J. 1949. Condition and management of rangeland based on quantitative ecology. *Journal of Range Management* 2:104–115.
- ELMQVIST, T., C. FOLKE, M. NYSTRÖM, G. PETERSON, J. BENGTSSON, B. WALKER, AND J. NORBERG. 2003. Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 1:488–494.
- ESTELL, R. E., K. M. HAVSTAD, A. F. CIBILS, E. L. FREDRICKSON, D. M. ANDERSON, T. S. SCHRADER, AND D. K. JAMES. 2012. Increasing shrub use by livestock in a world with less grass. *Rangeland Ecology & Management* 65:553–562.
- EVERS, L., R. F. MILLER, M. HEMSTROM, J. MERZENICH, R. NEILSON, AND P. DOESCHER. 2011. Estimating historical sage-grouse habitat abundance using a state-and-transition model. *Natural Resources and Environmental Issues* 17(1):16. Available at: <http://digitalcommons.usu.edu/nrei/vol17/iss1/16>.
- EVINER, V., T. K. GARBACH, J. H. BATY, AND S. A. HOSKINSON. 2012. Measuring the effects of plants on ecosystem services: challenges and prospects. *Invasive Plant Science and Management* 5:125–136.
- FERNANDEZ-GIMENEZ, M., AND B. BATBUYAN. 2004. Law and disorder: local implementation of Mongolia's Land Law. *Development and Change* 35:141–166.
- FLEISHMAN, E., D. E. BLOCKSTEIN, J. A. HALL, M. B. MASCIA, M. A. RUDD, J. M. SCOTT, W. J. SUTHERLAND, A. M. BARTUSKA, A. G. BROWN, C. A. CHRISTEN, J. P. CLEMENT, D. DELLA SALA, C. S. DUKE, M. EATON, S. J. FISKE, H. GOSNELL, J. C. HANEY, M. HUTCHINS, M. L. KLEIN, J. MARQUEE, B. R. NOON, J. R. NORDGREN, P. M. ORBUCH, J. POWELL, S. P. QUARLES, K. A. SATERSON, C. C. SAVITT, B. A. STEIN, M. S. WEBSTER, AND A. VEDDER. 2011. Top 40 priorities for science to inform US conservation and management policy. *BioScience* 61:290–300.
- FOLKE, C. 2006. Resilience, the emergence of a perspective for social–ecological systems analyses. *Global Environmental Change* 16:253–267.
- FOLKE, C., S. CARPENTER, B. WALKER, M. SCHEFFER, T. CHAPIN, AND J. ROCKSTRÖM. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society* 15(4):20. Available at: <http://www.ecologyandsociety.org/vol15/iss4/art20/>.
- FUHLENDORF, S. D., D. M. ENGLE, R. D. ELMORE, R. F. LIMB, AND T. G. BIDWELL. 2012. Conservation of pattern and process: developing an alternative paradigm of rangeland management. *Rangeland Ecology & Management* 65:579–589.
- FUNTOWICZ, S. O., AND J. R. RAVETZ. 1993. Science for the post-normal age. *Futures* 25:739–755.
- GODFRAY, H. C. J., J. R. BEDDINGTON, I. R. CRUTE, L. HADDAD, D. LAWRENCE, J. F. MUIR, J. PRETTY, S. ROBINSON, S. M. THOMAS, AND C. TOULMIN. 2010. Food security: the challenge of feeding 9 billion people. *Science* 327:812–818.
- GOMIERO, T., D. PIMENTEL, AND M. G. PAOLETTI. 2011. Is there a need for a more sustainable agriculture? *Critical Reviews in Plant Sciences* 30:6–23.
- GRAU, H. R., N. I. GASPARRI, AND T. M. AIDE. 2008. Balancing food production and nature conservation in the Neotropical dry forests of northern Argentina. *Global Change Biology* 14:985–997.
- GRIMM, N. B., J. M. GROVE, S. T. A. PICKETT, AND C. L. REDMAN. 2000. Integrated approaches to long-term studies of urban ecological systems. *BioScience* 50:571–584.
- HAVSTAD, K. M., D. P. C. PETERS, R. SKAGGS, J. BROWN, B. BESTELMEYER, E. FREDRICKSON, J. HERRICK, AND J. WRIGHT. 2007. Ecosystem services to and from rangelands of the western United States. *Ecological Economics* 64:261–268.
- HERRICK, J. E., B. T. BESTELMEYER, S. R. ARCHER, A. J. TUGEL, AND J. R. BROWN. 2006. An integrated framework for science-based arid land management. *Journal of Arid Environments* 65:319–335.
- HERRICK, J. E., J. R. BROWN, B. T. BESTELMEYER, S. S. ANDREWS, G. BALDI, J. DAVIES, M. DUNIWAY, K. M. HAVSTAD, J. KARL, D. L. KARLEN, D. P. C. PETERS, J. N. QUINTON, C. RIGINOS, P. L. SHAVER, D. STEINAKER, AND S. TWOMLOW. 2012. Revolutionary land use change in the 21st century: is (rangeland) science relevant? *Rangeland Ecology & Management* 65:590–598.
- HOLLING, C. S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4:1–23.
- HOLMES, J. 2002. Diversity and change in Australia's rangelands: a postproductivist transition with a difference? *Transactions: Institute of British Geographers* 27:362–384.
- HUTCHINSON, B., J. PFANDER, J. TANAKA, AND J. CLARK. 2011. Rangelands West/Global Rangelands, eXtension Rangelands, and the Range Science Information System: a suite of new web resources. *Rangelands* 33(4):55–63.
- JONES, N. A., H. ROSS, T. LYNAM, P. PEREZ, AND A. LEITCH. 2011. Mental models: an interdisciplinary synthesis of theory and methods. *Ecology and Society* 16(1):46. Available at: <http://www.ecologyandsociety.org/vol16/iss1/art46/>.
- JUNTITI, M., D. RUSSEL, AND J. TURNPENNY. 2009. Evidence, politics and power in public policy for the environment. *Environmental Science and Policy* 12:207–215.
- KARL, J. W., K. COLSON, AND H. SWARTZ. 2011. Rangeland assessment and monitoring methods guide. *Rangelands* 33(4):48–54.
- KARL, J. W., J. E. HERRICK, AND D. M. BROWNING. 2012. A strategy for rangeland management based on best available knowledge and information. *Rangeland Ecology & Management* 65:638–646.
- KNAPP, C. N., M. E. FERNANDEZ-GIMENEZ, D. D. BRISKE, B. T. BESTELMEYER, AND X. B. WU. 2011a. An assessment of state-and-transition models: perceptions following two decades of development and implementation. *Rangeland Ecology & Management* 64:598–606.
- KNAPP, C. N., M. E. FERNANDEZ-GIMENEZ, E. KACHERGIS, AND A. RUDEEN. 2011b. Using participatory workshops to integrate state-and-transition models created with local knowledge and ecological data. *Rangeland Ecology & Management* 64:158–170.
- KOONTZ, T. M., AND J. BODINE. 2008. Implementing ecosystem management in public agencies: lessons from the U.S. Bureau of Land Management and the Forest Service. *Conservation Biology* 22:60–69.
- KREMEN, C. 2005. Managing ecosystem services: what do we need to know about their ecology? *Ecology Letters* 8:468–479.
- LAWTON, J. H. 2007. Ecology, politics and policy. *Journal of Applied Ecology* 44:461–474.
- LETNIC, M., AND C. R. DICKMAN. 2010. Resource pulses and mammalian dynamics: conceptual models for hummock grasslands and other Australian desert habitats. *Biological Reviews* 85:501–521.
- LUDWIG, D. 2001. The era of management is over. *Ecosystems* 4:758–764.
- LUDWIG, D., R. HILBORN, AND C. WALTERS. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. *Science* 260:17–36.
- LUDWIG, D., M. MANGEL, AND B. HADDAD. 2001. Ecology, conservation, and public policy. *Annual Review of Ecology and Systematics* 32:481–517.
- LYNAM, T. J. P., AND M. STAFFORD SMITH. 2004. Monitoring in a complex world: seeking slow variables, a scaled focus, and speedier learning. *African Journal of Range & Forage Science* 21:69–78.
- MARX, S. M., E. U. WEBER, B. S. ORLOVE, A. LEISEROWITZ, D. H. KRANTZ, C. RONCOLI, AND J. PHILLIPS. 2007. Communication and mental processes: experiential and analytic processing of uncertain climate information. *Global Environmental Change* 17:47–58.
- MEASHAM, T. G., L. BRAKE, C. J. ROBINSON, S. LARSON, C. RICHARDS, AND T. F. SMITH. 2011. NRM engagement between remote dryland communities and government agencies: success factors from Australia. *Journal of Arid Environments* 75:968–973.
- MERVIS, J. 2012. Agencies rally to tackle big data. *Science* 336:22.
- MILLENNIUM ECOSYSTEM ASSESSMENT. 2005. Ecosystems and human well-being: synthesis. Washington, DC, USA: Island Press. 137 p.
- MONACO, T. A., T. A. JONES, AND T. L. THUROW. 2012. Identifying rangeland restoration targets: an appraisal of challenges and opportunities. *Rangeland Ecology & Management* 65:599–605.
- MORTON, L., E. REGEN WRIGHT, D. M. ENGLE, J. R. MILLER, AND R. N. HARR. 2010. Perceptions of landowners concerning conservation grazing, fire, and eastern redcedar management in tallgrass prairie. *Rangeland Ecology & Management* 63:645–654.
- MORTON, S. R., O. HOEGH-GULDBERG, D. B. LINDENMEYER, M. HARRISS OLSON, L. HUGHES, M. T. McCULLOCH, S. MCINTYRE, H. A. NIX, S. M. PROBER, D. A. SAUNDERS, A. N. ANDERSEN, M. A. BURGMAN, E. C. LEFROY, E. C. LONSDALE, I. LOWE, A. J. McMICHAEL, J. S. PARSLAW, W.

- STEFFEN, J. E. WILLIAMS, AND J. C. Z. WOJNARSKI. 2009. The big ecological questions inhibiting effective environmental management in Australia. *Austral Ecology* 34:1–9.
- NANDINTSETSEG, B., J. S. GREENE, AND C. E. GOULDEN. 2007. Trends in extreme daily precipitation and temperature near Lake Hövsgöl, Mongolia. *International Journal of Climatology* 27:341–347.
- NELSON, E., G. MENDOZA, J. REGETZ, S. POLASKY, H. TALLIS, D. R. CAMERON, K. M. A. CHAN, G. C. DAILY, J. GOLDSTEIN, P. M. KAREIVA, E. LONSDORF, R. NAIDOO, T. H. RICKETTS, AND M. R. SHAW. 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment* 7:4–11.
- NATIONAL RESEARCH COUNCIL. 1994. Rangeland health: new methods to classify, inventory and monitor rangelands. Washington, DC, USA: National Academy Press. 180 p.
- OLENICK, K. L., U. P. KREUTER, AND J. R. CONNER. 2005. Texas landowner perceptions regarding ecosystem services and cost-share land management programs. *Ecological Economics* 57:337–345.
- PAULSON, D. 1998. Collaborative management of public rangeland in Wyoming: lessons in co-management. *Professional Geographer* 50:301–315.
- PETERS, D. P. C., J. BELNAP, J. A. LUDWIG, S. L. COLLINS, J. PARUELO, M. T. HOFFMAN, AND K. M. HAVSTAD. 2012. How can science be general, yet specific? the conundrum of rangeland science in the 21st century. *Rangeland Ecology & Management* 65:613–622.
- PETERS, D., B. BESTELMEYER, E. FREDRICKSON, J. HERRICK, C. MONGER, AND K. HAVSTAD. 2006. Disentangling complex landscapes: new insights to forecasting arid and semiarid system dynamics. *BioScience* 56:491–501.
- PICKETT, S. T. A., J. KOLASA, AND C. G. JONES. 2007. Ecological understanding: the nature of theory and the theory of nature. Boston, MA, USA: Elsevier. 233 p.
- POLASKY, S., S. R. CARPENTER, C. FOLKE, AND B. KEELER. 2011. Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology and Evolution* 26:398–404.
- PULLEN, A. S., T. M. KNIGHT, D. A. STONE, AND K. CHARMAN. 2004. Do conservation managers use scientific evidence to support their decision-making? *Biological Conservation* 119:245–252.
- RAUDSEPP-HEARNE, C., G. D. PETERSON, AND E. M. BENNETT. 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences USA* 107:5242–5247.
- REED, M. S. 2008. Stakeholder participation for environmental management: a literature review. *Biological Conservation* 141:2417–2431.
- REED, M., A. DOUGILL, AND T. BAKER. 2008. Participatory indicator development: what can ecologists and local communities learn from each other? *Ecological Applications* 18:1253–1269.
- REED, M. S., A. C. EVELY, G. CUNDILL, I. FAZEY, J. GLASS, A. LAING, J. NEWIG, B. PARRISH, C. PRELL, C. RAYMOND, AND L. C. STRINGER. 2010. What is social learning. ? *Ecology and Society* 15(4):r1. Available at: <http://www.ecologyandsociety.org/vol15/iss4/resp1/>.
- REID, W. V., D. CHEN, L. GOLDFARB, H. HACKMANN, Y. T. LEE, K. MOKHELE, E. OSTROM, K. RAIWIO, J. ROCKSTRÖM, H. J. SCHELLNHUBER, AND A. WHYTE. 2010. Earth system science for global sustainability: grand challenges. *Science* 330:916–917.
- REYNOLDS, J. F., D. M. STAFFORD SMITH, E. F. LAMBIN, B. L. TURNER, M. MORTIMORE, S. P. J. BATTERBURY, T. E. DOWNING, H. DOWLATABADI, R. FERNANDEZ, J. E. HERRICK, E. HUBER-SANNWALD, H. JIANG, R. LEEMANS, T. LYNAM, F. T. MAESTRE, M. AYARZA, AND B. WALKER. 2007. Global desertification: building a science for dryland development. *Science* 316:847–851.
- ROCKSTROM, J., W. STEFFEN, K. NOONE, A. PERSSON, F. S. CHAPIN III, E. F. LAMBIN, T. M. LENTON, C. FOLKE, H. J. SCHELLNHUBER, B. NYKVIST, C. A. WIT, T. HUGHES, S. LEEUW, H. RODEHE, S. SORLIN, P. K. SYNDER, R. COSTANZA, U. SVEDIN, M. FALKENMARK, L. KARLBERG, R. W. CORELL, V. J. FABRY, J. HANSEN, B. WALKER, D. LIVERMAN, K. RICHARDSON, P. CRUTZEN, AND J. A. FOLEY. 2009. A safe operating space for humanity. *Nature* 462:472–475.
- SANCHEZ, P. A., S. AHAMED, F. CARRE, A. E. HARTEMINK, J. HEMPEL, J. HUISING, P. LAGACHERIE, A. B. McBRATNEY, M. J. MCKENZIE, M. DE LOURDES MENDONCAP-SANTOS, B. MINASNY, L. MONTARARELLA, P. OKOTH, C. A. PALM, J. D. SACHS, K. D. SHEPHERD, T.-G. VAGEN, B. VANLAUWE, M. G. WALSH, L. A. WINOWIECKI, AND G.-L. ZHANG. 2009. Digital soil map of the world. *Science* 325:680–681.
- SAYRE, N., W. DEBUYS, B. T. BESTELMEYER, AND K. M. HAVSTAD. 2012. “The Range Problem” after a century of rangeland science: new research themes for altered landscapes. *Rangeland Ecology & Management* 65:545–552.
- SHELEY, R. L., J. M. MANGOLD, AND J. L. ANDERSON. 2006. Potential for successional theory to guide restoration of invasive-plant-dominated rangeland. *Ecological Monographs* 76:365–379.
- SHERIDAN, T. E. 2007. Embattled ranchers, endangered species, and urban sprawl: The political ecology of the new American West. *Annual Review of Anthropology* 36:121–138.
- SMITH, R. J., D. VERISSIMO, N. LEADER-WILLIAMS, R. M. COWLING, AND A. T. KNIGHT. 2009. Let the locals lead. *Nature* 462:280–281.
- STAFFORD SMITH, D. M., G. M. McKEON, I. W. WATSON, B. K. HENRY, G. S. STONE, W. B. HALL, AND S. M. HOWDEN. 2007. Learning from episodes of degradation and recovery in variable Australian rangelands. *Proceedings of the National Academy of Sciences USA* 104:20690–20695.
- STAFFORD SMITH, M. 2008. The “desert syndrome”—causally-linked factors that characterise outback Australia. *The Rangeland Journal* 30:3–14.
- STAFFORD SMITH, M., C. JAMES, M. MCGREGOR, AND J. FERGUSON. 2008. Guest editorial: building a science of desert living. *The Rangeland Journal* 30:1–2.
- STEELE, C. M., B. T. BESTELMEYER, P. L. SMITH, S. YANOFF, AND L. M. BURKETT. 2012. Spatially-explicit representation of state-and-transition models. *Rangeland Ecology & Management* 65:213–222.
- STUTH, J. W., J. ANGERER, R. KAITHO, A. JAMA, AND R. MARAMBII. 2005. Livestock Early Warning System for Africa rangelands. In: V. K. Boken, A. P. Cracknell, and R. L. Heathcote [eds.]. Monitoring and predicting agricultural drought: a global study. New York, NY, USA: Oxford. p. 283–296.
- SUSSKIND, L., A. E. CAMACHO, AND T. SCHENK. 2012. A critical assessment of collaborative adaptive management in practice. *Journal of Applied Ecology* 49:47–51.
- SUTHERLAND, W. J., W. M. ADAMS, R. B. ARONSON, R. AVELING, T. M. BLACKBURN, S. BROAD, G. CEBALLOS, I. M. COTE, R. M. COWLING, G. A. B. DA FONSECA, E. DINERSTEIN, P. J. FERRARO, E. FLEISHMAN, C. GASCON, M. HUNTER, J. HUTTON, P. KAREIVA, A. KURIA, D. W. MACDONALD, K. MACKINNON, F. J. MADGWICK, M. B. MASCIA, J. McNEELY, E. J. MILNER-GULLAND, S. MOON, C. G. MORLEY, S. NELSON, D. OSBORN, M. PAI, E. C. M. PARSONS, L. S. PECK, H. POSSINGHAM, S. V. PRIOR, A. S. PULLIN, M. R. W. RANDES, J. RANGANATHAN, K. H. REDFORD, J. P. RODRIGUEZ, F. SEYMOUR, J. SOBEL, N. S. SODHI, A. STOTT, K. VANCE-BORLAND, AND A. R. WATKINSON. 2009. One hundred questions of importance to the conservation of global biological diversity. *Conservation Biology* 23:557–567.
- TANAKA, J. A., M. BRUNSON, AND L. A. TORELL. 2011. A social and economic assessment of rangeland conservation practices. In: D. D. Briske [ed.]. Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps. Lawrence, KS, USA: Allen Press. p. 371–422.
- VIVONI, E. R. 2012. Spatial patterns, processes and predictions in ecohydrology: integrating technologies to meet the challenge. *Ecohydrology* 5:235–241.
- WALKER, B., C. S. HOLLING, S. R. CARPENTER, AND A. KINZIG. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society* 9(2):5. Available at: <http://www.ecologyandsociety.org/vol9/iss2/art5/>.
- WALKER, B. H., N. ABEL, J. M. ANDERIES, AND P. RYAN. 2009. Resilience, adaptability, and transformability in the Goulburn-Broken Catchment, Australia. *Ecology and Society* 14(1):12. Available at: <http://www.ecologyandsociety.org/vol14/iss1/art12/>.
- WALKER, B. H., AND D. SALT. 2006. Resilience thinking: sustaining ecosystems and people in changing world. Washington, DC, USA: Island Press. 174 p.
- WALKER, P., AND P. HURLEY. 2004. Collaboration derailed: the politics of “community-based” resource management in Nevada County. *Society & Natural Resources* 17:735–751.
- WALTNER-TOEWS, D., J. J. KAY, C. NEUDOERFFER, AND T. GITAU. 2003. Perspective changes everything: managing ecosystems from the inside out. *Frontiers in Ecology and the Environment* 1:23–25.
- WEIBLE, C. M., P. A. SABATIER, AND A. PATTISON. 2010. Harnessing expert-based information for learning and the sustainable management of complex socio-ecological systems. *Environmental Science and Policy* 13:522–534.
- WEICHELSEGARTNER, J., AND R. KASPERSON. 2010. Barriers in the science-policy-practice interface: toward a knowledge-action-system in global environmental change research. *Global Environmental Change* 20:266–277.
- WILLIAMS, J. W., AND S. T. JACKSON. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* 5:475–482.